Protostellar fragmentation in a power-law density distribution[*]

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ABSTRACT

Hydrodynamical calculations in three space dimensions of the collapse of an isothermal, rotating 1 $M_\odot$ protostellar cloud are presented. The initial density stratification is a power law with density $\rho \propto r^{-p}$, with $p = 1$. The case of the singular isothermal sphere ($p = 2$) is not considered; however $p = 1$ has been shown observationally to be a good representation of the density distribution in molecular cloud cores just before the beginning of collapse. The collapse is studied with two independent numerical methods, an SPH code with 200,000 particles, and a finite-difference code with nested grids which give high spatial resolution in the inner regions. Although previous numerical studies have indicated that such a power-law distribution would not result in fragmentation into a binary system, both codes show, in contrast, that multiple fragmentation does occur in the central regions of the protostar. Thus the process of binary formation by fragmentation is shown to be consistent with the fact that a large fraction of young stars are observed to be in binary or multiple systems.

1 INTRODUCTION

This paper considers a long-standing problem regarding binary formation by fragmentation of a collapsing, rotating cloud, namely, that observed molecular cloud cores in star forming regions are sufficiently centrally condensed so that they would not fragment according to numerical calculations, yet these regions have a high proportion of binary systems. Fuller & Myers (1992), in a survey of cloud cores, some of which are in Taurus, found a density distribution $\rho \propto r^{-p}$, where $p \approx 1.6$, independent of whether the cores had IR sources in them or not. The survey by Ward-Thompson et al (1994), in the dust continuum, of cores without infrared sources showed $p \approx 1.25$ in the inner regions and $p \approx 2.0$ in the outer regions, where the 'inner' region refers to $r < 0.05$ pc. One of these cores, L1689B, has been reobserved at 1.3 mm at higher spatial and angular resolution (André, Ward-Thompson, & Motte 1996) and the result has been confirmed: the central regions have $p \approx 1$. In addition, theoretical studies (Lizano & Shu 1989; Tomisaka, Ikeuchi, & Nakamura 1990; Ciolek & Mouschovias 1994; Basu & Mouschovias 1994) of the quasistatic evolution of magnetically supported molecular clouds end up with cores having a centrally condensed distribution at the onset of collapse.

However, according to previous three-dimensional hydrodynamical calculations of the collapse of such cores (Boss 1987; Myhill & Kaula 1992) they do not fragment if they are initially uniformly rotating and have $p = 1$. The same conclusion is reached for clouds with $p = 2$, an often-used initial condition for numerical calculations of star formation, and in this case the conclusion is bolstered by a linear stability analysis (Tsai & Bertschinger 1989). Although Myhill & Kaula (1992) do find fragmentation with an initially differentially rotating cloud ($p = 1$ or 2), there is no observational evidence that clouds at the onset of collapse are differentially rotating, and furthermore, it is expected from theory (Basu & Mouschovias 1994) that the initial clouds will be in near-uniform rotation because of the effects of magnetic braking.

From what has just been said one would deduce, for example for the Taurus-Aurigae star-forming region, that very few of the formed stars would be in binary systems. However in fact almost all of the stars in that region are multiple, as deduced from the observations of several groups (Ghez, Neugebauer, & Matthews 1993; Leinert et al 1993; Simon et al 1995; Brandner et al 1996; Mathieu 1994). In other star-forming regions (Brandner et al 1996) the binary fraction is not quite so high as in Taurus, but nevertheless it is comparable to that among nearby solar-type main-sequence stars (Duquennoy & Mayor 1991). It is a generally accepted conclusion that most of these binaries must have formed during the protostellar collapse, perhaps by fragmentation; Fuller, Ladd, & Hodapp (1996) have recently discovered a binary protostar in the earliest stages of formation.

In the present paper we consider the question of whether fragmentation during protostellar collapse is, in fact, a viable mechanism for binary formation. Although many previous studies of three-dimensional protostar collapse have resulted in fragmentation (Boss 1993, 1996; Burkert & Bodenheimer 1993,1996, Bonnell & Bastien 1993, Bonnell & Bate 1994, Monaghan 1994; Miyama 1992; Turner et al 1995; Nelson & Papaloizou 1993; Sigalotti & Klapp 1994), the initial assumed density variation with distance from the centre was generally either uniform or a mild exponential (Boss 1991, 1993),that is, less centrally condensed than the distributions suggested by observations. We calculate the collapse of

isothermal, rotating clouds, without magnetic fields, with two different three-dimensional hydrodynamic codes, starting with the density distribution $p = 1$ and with uniform rotation. The initial density distribution is assumed to be spherically symmetric with a small nonaxisymmetric perturbation. The purpose of our calculation is to calculate the collapse with much higher spatial resolution and to carry it over a longer time period than earlier numerical calculations to see if fragmentation does in fact occur. We also test to see if fragmentation properties depend on the assumed angular momentum of the cloud.

2 THE COMPUTATIONAL METHOD AND INITIAL CONDITIONS

2.1 Grid code

The finite difference method is essentially the same as that described by Burkert & Bodenheimer (1993, 1996). The calculations are performed on a 3-dimensional Eulerian, Cartesian grid; the advection scheme is based on second-order monotonic transport (van Leer 1977). The full computational region is represented by a standard grid, composed of 64^3 grid cells equally spaced in all directions. For improved resolution of the inner regions, four Cartesian nested concentric subgrids were superimposed on the standard grid, giving a ratio of total cloud size to the size of the smallest zone of 1000 or 2000. The linear scale on a given subgrid is reduced by a factor of 2 or 4 with respect to the next larger grid. The grid structure is set up at the beginning of the calculation and left fixed during the entire run. An artificial viscosity of the type described by Colella & Woodward (1984) is added; its main effect is to suppress a rapid increase in the density at centres of fragments. Unlike the calculations of Burkert & Bodenheimer (1996) there is no symmetry assumed with respect to the z-axis, although the configuration is assumed to be symmetric with respect to the equatorial plane.

An important difference between the calculations reported in this paper and most previous fragmentation calculations is that an additional numerical stability criterion is incorporated. Klein, Truelove, & McKee (1996) have pointed out that numerical fragmentation could occur in a calculation if the local zone size is larger than the local Jeans length. In their adaptive mesh calculation they simply dynamically rezone to a sufficiently high level of accuracy so that the criterion is always satisfied. In our calculations, to avoid using an excessively large number of zones, we introduce an artificial heating at high densities, so that if the mass of a zone exceeds the local Jeans mass, the zone is heated until its mass is less than the local Jeans mass. The heating procedure affects only the regions of highest density, which in general are already part of fragments, and tests of calculations with and without heating show very little difference in the results.

The Jeans mass is given by (Spitzer 1978) as ρl_J^3 where l_J is the local Jeans length; thus

$$M_J = 2.44 \times 10^{23} (\frac{T}{\mu})^{3/2} \rho^{-1/2} \quad \text{g} \tag{1}$$

If the zone size is Δ, then the requirement that the zone mass $\rho \Delta^3 < M_J$ defines a critical

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density ρ_c:

$$\rho < \rho_c = \frac{3.905 \times 10^{15}}{\Delta^2}\left(\frac{T}{\mu}\right) \quad \text{g cm}^{-3} \tag{2}$$

If $\rho > \rho_c$, then the zone is heated so that its new sound speed c_s is

$$c_s^2 = \frac{2.561 \times 10^{-16}\rho\Delta^2 R_g}{\eta_\rho} \quad \text{cm}^2 \text{ s}^{-2} \tag{3}$$

Here R_g is the gas constant and η_ρ is a safety factor, taken to be 0.5, so that the heating starts at somewhat lower densities than ρ_c.

2.2 SPH code

The SPH calculations were performed using a three-dimensional code based on a version originally developed by Benz (1990; Benz et al. 1990). The standard form of artificial viscosity is used (Monaghan & Gingold 1983; Benz 1990; Monaghan 1992), with the parameters $\alpha_v = 1$ and $\beta_v = 2$. The smoothing lengths of particles are variable in time and space, subject to the constraint that the number of neighbours for each particle must remain approximately constant at $N_{\text{neigh}} = 50$. The SPH equations are integrated using a second-order Runge-Kutta-Fehlberg integrator.

Two major modifications have been made to the original code. First, individual time steps are used for each particle (Bate, Bonnell & Price 1995) rather than a single time step for all particles. The result is a great saving in computational time for simulations where there is a large density contrast (e.g. fragmentation calculations). Second, gravitational forces and a particle's nearest neighbours are found by using either a tree, as in the original code, or the special-purpose GRAvity-piPE (GRAPE) hardware. The implementation of SPH using the GRAPE closely follows that described by Steinmetz (1996). Using the GRAPE attached to a Sun SPARCstation 20 workstation typically results in a factor of 5 improvement in speed over the workstation alone. The calculation presented here was performed using the GRAPE.

We use the polytropic equation of state $P = K\rho^\gamma$, where K is a constant that depends on the entropy of the gas. The polytropic constant γ varies with density as

$$\gamma = 1, \qquad \rho \leq \rho_{c2} = 10^{-12} \text{ g cm}^{-3},$$

$$\gamma = \frac{5}{3}, \qquad \rho > \rho_{c2} = 10^{-12} \text{ g cm}^{-3}, \tag{4}$$

and K is defined such that, when the gas is isothermal ($\rho \leq \rho_{c2}$), $K = c_s^2$ with the sound speed $c_s = 2.037 \times 10^4$ cm s^{-1}. Heating the gas when $\rho > \rho_{c2}$ serves two purposes. First, with a purely isothermal equation of state, a non-rotating fragment collapses to infinite density. Thus, a fragmentation calculation must be stopped when the first fragment is formed. If the gas is heated, however, the collapse of a fragment is halted and the calculation can be followed further. Second, heating of the gas is required so that the minimum mass that can be resolved ($\approx 2N_{\text{neigh}}$ times the particle mass) is always less than a Jeans mass. If this criterion is not met fragmentation may be artificially induced

(Bate & Burkert, in preparation). This criterion is similar to that used for the grid code. For the calculation presented in this paper 200,000 equal-mass particles are used. Thus, from equation 1, a Jeans mass is less than the mass of $2N_{neigh}$ particles when $\rho \gtrsim 7 \times 10^{-12}$ g cm^{-3}. Heating the gas for $\rho > \rho_{c2}$ ensures a Jeans mass is always resolved.

2.3 Initial conditions

The protostar in the present calculation is assumed to be isothermal in space and time. The initial conditions are specified by the ratios α and β, which are, respectively, the thermal and rotational energies divided by the absolute value of the gravitational energy, and by the angular momentum distribution, the size and form of the initial perturbation, and the form of the density distribution. The latter is taken to be

$$\rho(r) = \rho_0 \left(\frac{r_0}{r}\right)^p \tag{5}$$

with $p = 1$. Here r is the distance to the origin and ρ_0 and r_0 are constants. The form of the perturbed profile is

$$\rho_p(r) = \rho(r)[1 + a_1 \cos(2\phi)] \tag{6}$$

where a_1 is the amplitude of the perturbation and ϕ is the azimuthal angle about the rotation (z) axis. In all cases presented here the a_1 is set to 0.1, the cloud mass M_{tot} is set to 1.0 M$_\odot$, $r_0\rho_0 = 0.1273$ g cm^{-2}, the angular velocity Ω is uniform, and the radius R of the original sphere is 5×10^{16} cm. The sound speed $c_s = 2.037 \times 10^4$ cm s^{-1}; thus the value of α for all calculations was 0.35.

3 RESULTS

3.1 Analytic discussion

A spherically symmetric, isothermal gas cloud with a power-law density distribution as given by equation 5 is a somewhat unphysical initial condition for $0 < p < 2$ because there exists a critical radius $r_{crit} > 0$ inside which the gas will initially expand even if centrifugal forces are neglected. Within r_{crit} the pressure gradient initially exceeds the gravitational force:

$$-\frac{c^2}{\rho} \frac{\partial \rho}{\partial r} \geq \frac{GM(r)}{r^2} \tag{7}$$

where $M(r)$ is the total mass inside r and equality holds for $r = r_{crit}$. Given the density distribution of equation 5 and using equation 7, we find

$$r_{crit} = R \left(\frac{2p(3-p)\alpha}{3(5-2p)}\right)^{\frac{1}{2-p}} \tag{8}$$

which is valid for $0 \leq p < 2$.

Figure 1 shows r_{crit}/R and the fractional mass of the expanding region $M(r_{crit})/M_{tot}$ as a function of p for different values of α. Note that all power-law profiles with $0 < p < 2$, even with small values of α, have an initially expanding core. For the present case, where $\alpha = 0.35$ and $p = 1$, $r_{crit}/R = 0.156$ and $M(r_{crit})/M_{tot} = 0.024$.

3.2 Fragmentation, grid code, high beta

The first run was calculated with $\beta = 0.23$ on four subgrids, each $128 \times 128 \times 64$ zones in the (x, y, z) directions, respectively, which had radii of 2.50×10^{16} cm, 1.25×10^{16} cm, 6.25×10^{15} cm, and 3.125×10^{15} cm. The resolution on the finest grid is 4.88×10^{13} cm. Although the initial central density was 6×10^{-15} g cm^{-3} the initial expansion phase, which affects the inner 25% of the radius, results in a reduction of the central density to about 2×10^{-17} g cm^{-3}. The density and velocity distributions on the first subgrid at a time 4.3×10^{11} s are shown in Figure 2. At this time the expanding central region has nearly reached its maximum extent, and is about to resume collapse. The density profile is markedly less steep in this region than in the original cloud. The free-fall time in the central regions is now 4.4×10^{11} s.

The collapse then proceeds through more than six orders of magnitude increase in the central density before any signs of fragmentation begin to appear. Figure 3 shows the development of the central region (the innermost subgrid) starting at 1.176×10^{12} s from the beginning of the calculation. In Figure 3a a definite central density maximum is present. A small region around it has formed a flattened disk structure and a spiral-arm pattern. At the end points of the spiral pattern one can already see the development of two condensations which accrete material until they become self-gravitating. Figure 3b shows the original central density maximum connected by inner spiral arms to the newly-formed binary. Outside this region an outer spiral pattern has developed and a circum-triple disk is beginning to form. This high-density disk has become well-developed a short time later (Fig. 3c). At that time the symmetry of the inner system is broken as a result of small numerical perturbations and the triple system rearranges itself into a more stable hierarchical system, with a close binary and a third object further out. At the outer edge of the disk two new density maxima are visible, triggered by the interaction of the outer spiral arms. One of these maxima finally develops into an outer fragment, the other one is tidally disrupted and subsequently accreted by the outwards moving fragment of the previous inner triple system (Fig. 3d). At $t = 1.217 \times 10^{12}$ s the masses of the inner binary components are 0.055 and 0.025 $M_{\odot}$. The mass of the third component of the initial triple system is 0.017 $M_{\odot}$. The fourth fragment has a mass of 0.011 $M_{\odot}$.

At this time we stop the calculation; on the inner grid (scale 3×10^{15} cm) 90% of the total mass is included in the four fragments. However only a small fraction (12.4%) of M_{tot} is included in this region. We expect further interactions of these fragments to take place and possibly further fragmentation to occur on larger scales. But at this point it is clearly established that fragmentation has occurred, that some of the fragments will survive, and that the end result will be a multiple system.

3.3 Fragmentation, SPH code, high beta

To test whether or not the fragmentation is dependent on the numerical method, we perform the same calculation as in Section 3.2, but use Smoothed Particle Hydrodynamics (SPH). We use 200,000 equal-mass particles in order to resolve a Jeans mass at densities up to 10^{-12} g cm^{-3} while maintaining an isothermal equation of state. Beyond 10^{-12} g cm^{-3} the gas is heated so that a Jeans mass is always resolved.

The early evolution is identical to that calculated by the grid code, with an expansion in the centre of the cloud. The initial resolution in the centre is not as good as with the grid code; the maximum density is only 5×10^{-16} g cm^{-3}. This results from the fact that, with SPH, the resolution depends on the density. The smoothing length h, which gives the resolution, is defined so that $2h$ contains N_{neigh} particles. In the centre of the cloud, although the density formally goes to infinity as the radius goes to zero, the mass fraction is very small, and hence h must be large in order to contain N_{neigh} particles. Other than the difference in initial central density, however, the expansion is identical to that given by the grid code, with the same density minimum of 2×10^{-17} g cm^{-3} being reached before the expansion stops and the collapse begins.

During the collapse, the central density increases by more than six orders of magnitude, in agreement with the grid code. A central density maximum forms, and a disk of gas begins to form around it. The evolution of the central density maximum and its disk is shown in Figure 4. As soon as the disk appears around the central density maximum it is threaded by spiral arms (Fig. 4a). The arms continually wrap-up, interact and reform because of their differential rotation. Ultimately, density maxima form at the ends of the two arms leading to a binary around the central object (Fig. 4b). As higher angular momentum material falls in, spiral arms extend beyond the binary into a circum-triple disk. The symmetry of the triple system rapidly breaks, causing the outer spiral arms to become asymmetric. Again, density maxima form at the ends of these arms, however, due to the asymmetry, only one of these forms a fragment immediately; the other is temporarily disrupted (Fig. 4c). Eventually, this disrupted fifth density maxima does gather enough material to form a fifth fragment (Fig. 4d). Note that a fifth fragment appears also temporarily in the grid code. There, however, the somewhat different orbital evolution of the inner triple system leads to a merger (Fig. 3d).

The collapse and fragmentation follows the same pattern as with the grid code: a central object is formed, surrounded by a disk with spiral arms; fragments form at the end of the arms; the initial symmetry of the triple system breaks with one fragment moving outwards and the other two components forming a close binary system; a circum-triple disc forms, again threaded by spiral arms which fragment, with the details depending on symmetry breaking of the triple. The fact that this pattern of fragmentation has been produced with two completely different hydrodynamic codes demonstrates that the fragmentation is physical and not a numerical effect. Some details of the fragmentation differ between the two codes. The formation of the triple system occurs slightly earlier with the SPH code ($t = 1.155 \times 10^{12}$ s) than the grid code ($t = 1.176 \times 10^{12}$ s), before the disc has reached as large an extent. This earlier fragmentation is probably due to the different resolutions of the two codes, and the higher numerical noise that is present in the SPH code. The resolution of the two codes are almost identical at densities of

1.0×10^{-12} g cm^{-3} ($h = 4.0 \times 10^{13}$ cm, while the smallest grid cell has $\Delta = 4.9 \times 10^{13}$ cm). However, because the resolution of SPH depends on the density, for $\rho > 10^{-12}$ g cm^{-3} (i.e. in the spiral arms) the resolution is actually higher with SPH. The higher numerical noise of the SPH code results from the use of the GRAPE hardware which has less than single precision, whereas the grid code calculation (using a CRAY) performs gravitational calculations with double precision. This difference in numerical noise also leads to the symmetry of the triple system being broken quicker with the SPH code than the grid code.

We stop the calculation at the time 1.190×10^{12} s (Fig. 4d). At this point the disk and fragments contain 12.4% of M_{tot}. The fragment masses are 0.050 and 0.020 $M_\odot$ for the close binary and 0.018 $M_\odot$ for the third component of the initial triple system. These values are in excellent agreement with the results of the grid code. The two fragments which formed later on the far-left and far-right of Figure 4d have masses of 0.017 $M_\odot$ and 0.003 $M_\odot$, respectively. As with the grid code, mergers between fragments and further fragmentation are probable as the remaining material falls in, but the survival of a multiple system is likely.

3.4 Fragmentation, grid code, low beta

The runs discussed in the previous sections were calculated with fairly large rotation ($\beta = 0.23$). In order to check whether such a high value of β is crucial for fragmentation we have recalculated the same case with β reduced by a factor of 2. As the gas is now less rotationally supported we expect the system to become more centrally condensed. We therefore increased the resolution on the innermost grid by a factor of two, compared with the grid setup used in section 3.2. The four subgrids, each $128 \times 128 \times 64$ zones in the (x, y, z) directions, respectively, now have radii of 2.50×10^{16} cm, 6.25×10^{15} cm, 3.125×10^{15} cm, and 1.563×10^{15} cm. The resolution on the finest grid is 2.44×10^{13} cm.

Figure 5 shows snapshots of the evolution, which is qualitatively the same as for the high-β case, except that the scale of the region of initial fragmentation is reduced by a factor of 2. The initial development of spiral arms with density maxima at the ends is shown in Figure 5a. Figure 5b shows an inner triple system which formed in an analogous manner to the systems shown in Figures 3b and 4b. The symmetry then breaks as the original central density maximum approaches one of the new fragments, and a fourth fragment appears near the outer edge of the disk (Fig. 5c). A short time later five fragments are present (Fig. 5d) and the surrounding circum-fragment disk has expanded considerably. The calculation is stopped before the disk has grown to the size and mass where induced fragmentation on a larger scale (such as that shown in Fig. 3d) would be expected. However we obtain again multiple fragmentation; five distinct fragments, including one of very low mass, have clearly been established (Fig. 5d.) The typical separations are now of order 10^{15} cm as compared with 4×10^{15} cm at the end of the previous runs. The masses of the fragments in Figure 5d are (from left to right) .016, .017, .03, .002, and .016 $M_\odot$, slightly lower in total than in the previous case but including practically the entire mass on the innermost subgrid (scale 1.56×10^{15} cm). Note also that in this case the timescale of fragmentation is slightly shorter. This case was not run further because at $t = 1.007 \times 10^{12}$ s it is clear that fragmentation does occur even with the lower value of β.

The fragmentation is very likely not to be of numerical origin, since it all takes place

on the innermost grid and since heating is included to keep zone masses below the Jeans mass. In fact, heating plays only a very minor role in the sequence of events. From equation (2), the critical density above which heating takes place is $\rho_c = 3.27 \times 10^{-11}$ g cm^{-3}. The densities at the centres of the fragments in Figure 5d are typically 1.6×10^{-10} g cm^{-3}. and $\rho > \rho_c$ in only a few zones near the centres of the established fragments. The temperature increases to 98 K at the highest densities, which of course would tend to suppress fragmentation, but only in material which has already fragmented. The heating effect thus just slows the increase in the central densities. However the density of typical material in the vicinity of the fragments, which is the same as that from which the fragments originally condense, is about 10^{-12} g cm^{-3}. There the heating has no effect.

4 CONCLUSIONS

The main purpose of this paper has been to demonstrate that multiple fragmentation occurs even from an initial power-law density distribution which is similar to what is observed in molecular cloud cores. Our results differ from those of previous numerical simulations which, for initially uniform rotation, did not show evidence for fragmentation. However the initial expansion phase, which is an important factor as it leads to central expansion and to a core with a flat density distribution, had previously not been resolved. Thus in fact the actual initial conditions for collapse are unlikely to have $\rho \propto r^{-p}$ where $0 \leq p \leq 2$ but rather a distribution in which the central regions have a flatter profile. If such a configuration has solid-body rotation its angular momentum distribution will be somewhat different from that used here, but it is just as likely to fragment, as has been demonstrated by the calculations, for example, of Boss (1993).

In any case, high enough spatial resolution is required to bring out the detailed structure of the central regions. In addition, the calculations have to be carried out for a sufficient time beyond that when a condensed central object has formed so that a sufficient amount of mass with higher angular momentum has accumulated in the central disk region. Our results show that at least three to four fragments with unequal masses form, with the details depending on the value of β and the exact time of symmetry breaking which depends on the numerical noise.

It is promising that two entirely independent numerical techniques lead basically to the same result: the initial formation of a central triple system, subsequent symmetry breaking, and the formation of an outer disk with additional fragmentation on a larger scale. As the further evolution of the system is expected to be highly chaotic it will depend on the numerical technique and the local resolution which are not exactly identical in the two codes. It still has to be investigated by longer-term calculations to what extent the final stage will depend on all these details. Another important question is whether multiple fragmentation will occur in the extreme case of an $p = 2$ power law which does not lead to an initially expanding core.

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FIGURE CAPTIONS

Figure 1. The radius r_{crit}, inside of which a spherical power-law cloud initially expands, is shown (left panel), in units of the total cloud radius, as a function of the power-law index p, for various values of α, the initial ratio of thermal energy to the absolute value of the gravitational energy. The right panel shows the mass fraction inside r_{crit}, as a function of the same two parameters. From top to bottom, the curves correspond to $\alpha = 0.5, 0.4, 0.3, 0.2$, and 0.1.

Figure 2. Contours of equal density in the equatorial (x, y) plane at $z = 0$ at a time of 4.3 $\times 10^{11}$ s in the high-beta grid-code calculation. The first subgrid is shown. The maximum density is $\log \rho_{max} = -16.67$ and the contour interval is $\Delta \log \rho = 0.03$. Velocity vectors are shown with length proportional to speed; the maximum velocity V_{max} is 3.58×10^4 cm s^{-1}. The linear scale is given in cm.

Figure 3. Evolution of the high-beta case with the grid code. The innermost grid is shown. Symbols and curves have the same meaning as in Fig. 2. (a; upper left) $t = 1.176$ $\times 10^{12}$ s; $\log \rho_{max} = -10.3$; $\Delta \log \rho = 0.166$; $V_{max} = 1.95 \times 10^5$ cm s^{-1}. (b; upper right) t $= 1.190 \times 10^{12}$ s; $\log \rho_{max} = -10.2$; $\Delta \log \rho = 0.17$; $V_{max} = 2.57 \times 10^5$ cm s^{-1}. (c; lower left) $t = 1.209 \times 10^{12}$ s; $\log \rho_{max} = -10.1$; $\Delta \log \rho = 0.173$; $V_{max} = 3.17 \times 10^5$ cm s^{-1}. (d; lower right) $t = 1.217 \times 10^{12}$ s; $\log \rho_{max} = -10.1$; $\Delta \log \rho = 0.173$; $V_{max} = 3.67 \times 10^5$ cm s^{-1}.

Figure 4. Evolution of the high-beta case with the SPH code. Symbols and curves have the same meaning as in Fig. 2. (a; upper left) t=1.135×10^{12} s; $\log \rho_{max} = -10.0$; $\Delta \log \rho = 0.25$; $V_{max} = 2.44 \times 10^5$ cm s^{-1}. (b; upper right) t=1.160×10^{12} s; $\log \rho_{max} = -9.7$; $\Delta \log \rho = 0.25$; $V_{max} = 2.88 \times 10^5$ cm s^{-1}. (c; lower left) t=1.175×10^{12} s; $\log \rho_{max} = -9.6$ $\Delta \log \rho = 0.25$; $V_{max} = 3.66 \times 10^5$ cm s^{-1}. (d; lower right) t=1.190×10^{12} s; $\log \rho_{max} = -9.5$; $\Delta \log \rho = 0.25$; $V_{max} = 3.38 \times 10^5$ cm s^{-1}.

Figure 5. Evolution of the low-beta case with the grid code. The innermost grid is shown. Symbols and curves have the same meaning as in Fig. 2. (a; upper left) $t = 9.637 \times 10^{11}$ s; $\log \rho_{max} = -9.65$; $\Delta \log \rho = 0.219$; $V_{max} = 1.98 \times 10^5$ cm s^{-1}. (b; upper right) $t = 9.706$ $\times 10^{11}$ s; $\log \rho_{max} = -9.498$; $\Delta \log \rho = 0.224$; $V_{max} = 1.88 \times 10^5$ cm s^{-1}. (c; lower left) $t = 9.840 \times 10^{11}$ s; $\log \rho_{max} = -9.46$; $\Delta \log \rho = 0.225$; $V_{max} = 3.01 \times 10^5$ cm s^{-1}. (d; lower right) $t = 1.007 \times 10^{12}$ s; $\log \rho_{max} = -9.431$; $\Delta \log \rho = 0.226$; $V_{max} = 3.41 \times 10^5$ cm s^{-1}.